Holistic control system design for large mobile irrigation machines

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Abstract

Large mobile irrigation machines are self-propelled sprinkler irrigation systems which farmers are rapidly adopting due to the high precision of the irrigation application. Although it is highly desirable that control systems be used with such machines to both optimise the irrigation water volume applied to field crops and optimise water use efficiency, there are difficulties in applying classical control techniques. These are caused principally by the very slow speed of crop growth-response and stress-response dynamics; but in addition characteristics of the plant and infield sensors which are poorly known and provide only sparse, low-quality data for feedback control.

This paper outlines the operation of large mobile irrigation machines, analyses the limitations in the application of classical control approaches for their optimal use, and describes the methods that have been used to implement whole-system control via alternative (adaptive) approaches. These involve accommodation of sparse and unreliable input data and the application and evaluation of a range of irrigation volumes on different sub-areas of the field as on-the-go local system identification.

Introduction

Improving the efficiency of water use in agriculture is increasingly essential to maintain the profitability and sustainability of farms. This involves applying only the minimum necessary irrigation water to maintain or improve the yield of individual plants. Yield may be simply biomass (e.g. fodder crops), or may involve management of flower/fruit production in relation to vegetative growth (e.g. for cotton). Water available for irrigation may also be severely constrained.

A control system for irrigation determines the irrigation application to the crop using historical data or quantitative measurements of crop status (e.g. vegetative and reproductive growth), weather (e.g. temperature, solar radiation and humidity) and soil (e.g. soil moisture content), or some combination of these. Irrigation control systems may be implemented on a large mobile irrigation machine to provide automatic machine operation. As illustrated in Figure 1, large mobile irrigation machines in agriculture are configured as 'centre pivot' or 'lateral move' according to their motion and comprise a series of gantries, typically of 30-50 metre span, supported on bogie-mounted towers. Each gantry carries a series of sprinklers or on-surface delivery pipes fed from an overhead supply pipe. Gantries are connected end-to-end at a self-propelled wheeled bogie such that the assembly, typically up to 500 metres in length, moves through the crop at up to three metres per minute.

Fig. 1. Spans (gantries) of a lateral move irrigation machine (from CI 2010).

Basic control of the machine is usually limited to determining an appropriate speed of motion for the lead bogie according to the magnitude of the desired irrigation (depth of water to be applied) in relation to the water supply: all other bogies are autonomous and control their motion to maintain the span-to-span alignment angle at 180 degrees. In operation this arrangement is usually set up to provide uniform application of water, both spatially and throughout the duration of the irrigation, as the machine traverses the field. However, local irrigation requirements in a crop may be spatially variable due to soil type, soil properties, plant genetics, crop condition (stress, pest infestations etc.) and meteorological conditions. It follows that for almost any large field uniform irrigations will generally be sub-optimal and result in inefficient use of irrigation water.

Irrigation machines may be controlled to provide differential application of water according to irrigation requirements at different locations in the field. If the required irrigation amount can be determined at an appropriate local scale, control of the machine to provide spatially-varied water application can be achieved using machines fitted with variable flow-rate sprinklers / delivery pipes.

Limitations of sensing hardware and irrigation machines and dynamics of the crop present difficulties in applying classical control approaches to irrigation. This paper identifies the following limitations of classical control for irrigation and discusses the methods employed to overcome them:

- slow speed of crop dynamics;
- in-field variability sensing;
- characteristics of the irrigation machine;

- unknown process dynamics; and
- fundamental resource (irrigation water) constraints.

Holistic irrigation control

From a control perspective, the irrigation system comprises the machine (as water-delivery actuator) plus the crop being grown as characterised by the local plant response to water applied. Although the individual plants which constitute the crop are nominally identical, it is to be expected that individual plant responses will not be the same due to their differing (local) soil/water conditions and the growth history at each position in the field (Zhang et al. 2002). Furthermore, as plant response is a function of plant age, the combination of these phenomena indicate that unique system identification is not possible and adaptive approaches must be adopted.

Adaptive control systems automatically and continuously re-adjust (‘retune’) the controller to retain the desired performance of the system (e.g. Warwick 1993). Similarly, adaptive control strategies may be used to accommodate the various levels of data complexity normally found in irrigation (i.e. for the various combinations of plant, soil and weather data depending on data availability). By comparing adaptive control strategies, we may identify superior and hopefully optimal control strategies for irrigation, sensor variable requirements, and temporal and spatial scales requirements. The conceptual components of an adaptive control system for variable-rate irrigation are illustrated in Figure 2.

Adaptive irrigation control strategies (Figure 2) can use both historical data and real-time quantitative measurements of crop status, weather and soil, either singly or in combination, to locally adjust the irrigation application, as required, to account for temporal and spatial variability in the field. Figure 2 illustrates a generic irrigation control system that uses the full range of plant, weather and soil data for irrigation management. In Figure 2:

- the ‘decision support system’ embodies the control strategy;
- ‘actuation’ is the action of adjusting the irrigation volume and/or timing; and
- ‘application’ is the resulting physical amount and timing of water and fertiliser applied to the crop.

This process can be applied to both constant and spatially varied irrigation management at a range of time scales.

Limited applicability of classical control approaches

As noted, limitations of sensing hardware and irrigation machines, and dynamics of the crop, present difficulties in applying classical control approaches to the process of irrigation. Five areas are identified, as follows.

1. Slow speed of crop dynamics

The plant growth that occurs in response to an irrigation application may not be measurable for days after the irrigation (and commonly too small to be reliably

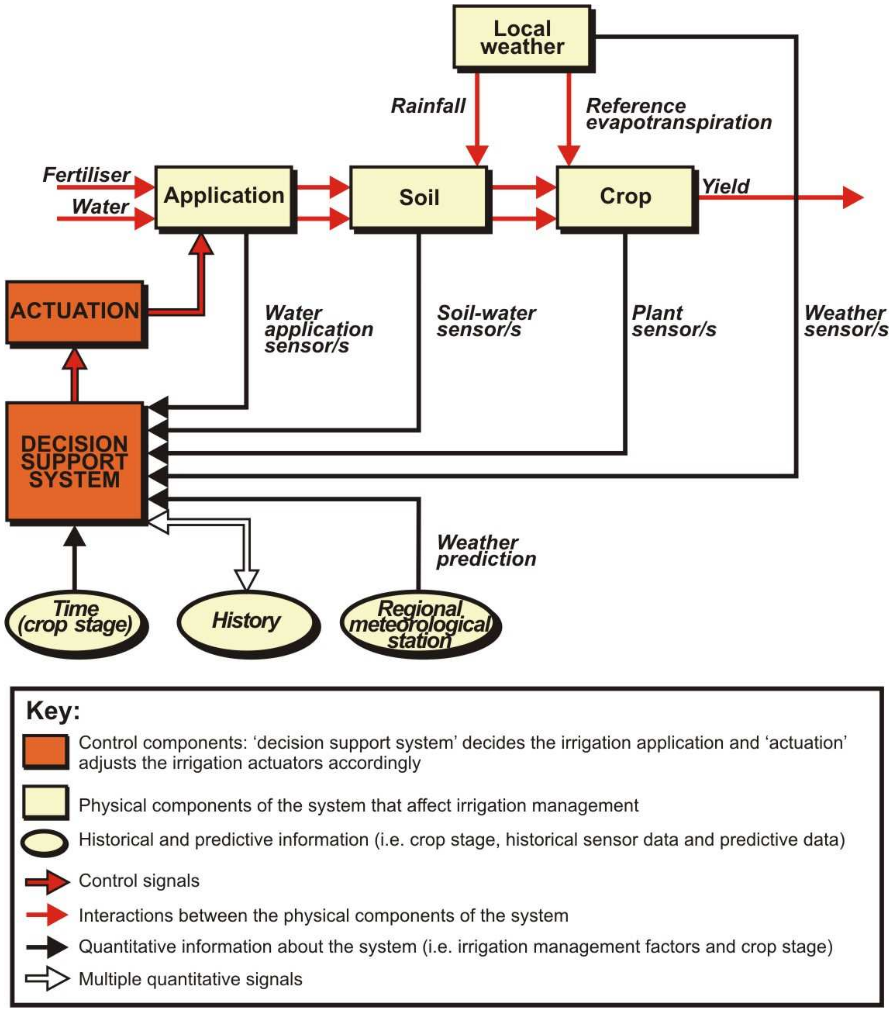

Fig. 2. Conceptual adaptive control system for variable-rate irrigation application (McCarthy et al. 2010)

measurable before the next irrigation event). However, plant data may provide a better indication of water requirement than soil and weather sensors (e.g. Kramer & Boyer 1995; Wanjura & Upchurch 2002; Jones 2004). This is because the plants essentially integrate the atmospheric and soil factors that affect the plant's water requirement. Hence, ideally, an irrigation control system should incorporate plant data with soil data (e.g. soil water status) to ensure the availability of appropriate feedback information before the subsequent irrigation event.

Likewise, the very slow response militates against the successful use of simple feedback control: classical feedback control systems are typically implemented in processes which are repeatedly executed and evaluated within milliseconds. And similarly, direct application of many commonplace system identification strategies is not efficient due to the different time scales in irrigation, again because irrigations occurs days apart and the crop's response to the irrigation is only reliably measurable after a number of days.

2. In-field variability sensing

Data required for an irrigation control system include weather (which indicates evaporative demand of the crop), soil moisture status and plant growth and health (stress) data. Soil moisture content sensors (e.g. Vellidis et al. 2008) and on-the-go water status and plant growth sensors (e.g. Peters & Evett 2008; McCarthy et al., 2009, respectively) have been developed which enable data measurement at a high spatial resolution.

Natural rainfall variability is often another unquantified variable. Typically an automatic weather station will measure rainfall for a single point nearby and in Australia some field crops (e.g. cotton) are grown in areas with highly spatially variable in-field rainfall (variation on a scale of 10s to 100s of metres, resulting from highly-localised cumulonimbus storms).

3. Characteristics of the irrigation machine

A fundamental irrigation system constraint is the irrigation machine capacity, which is defined as the maximum amount of water that can be applied to the field (litres per second). This translates into the depth of irrigation (millimetres) according to machine speed of movement. In turn the speed at which an irrigation machine traverses a field of given area determines the frequency of irrigation applications; for example, an irrigation machine with a capacity of 12 mm/day requires 2.5 days to apply irrigation water to a depth of 30 mm to the field.

Finally, it is significant that the irrigation machine as a water delivery actuator may not apply the desired irrigation volume. The irrigation outlets may require calibration to ensure the measured application corresponds to the desired irrigation output. Environmental factors (e.g. wind drift and evaporation losses) also influence the irrigation pattern from sprinklers.

4. Fundamental resource constraints

In practice, the volume of irrigation water available for irrigation is almost always limited by the fixed amount of water allocated to the grower. In turn, this may constrain the volume of irrigation water that can be applied to the field during each irrigation event. Hence, an irrigation control system must use the currently available water in the most efficient manner. This involves using the water to either: (i) fully irrigate a small area of the field chosen from plant condition (and grow the remainder of the crop in the field with no irrigation); or (ii) irrigate the whole field and increase the time between irrigation events and/or apply the minimum volume to maintain the crop.

5. Unknown process dynamics

Classical control practice often assumes that the dynamics of the process – in this case the soil-plant-atmosphere system – are, or at least may be, fully defined.

Crop production models (which relate growth to environmental factors) are available (e.g. OZCOT for cotton, Wells & Hearn 1992); however they require a calibration procedure to be reliably used to predict the response of the crop to irrigation. The model may be calibrated by iteratively adjusting crop and soil parameters until the crop model output converges to the measured data (measured and modeled data from a cotton model are shown in Figure 3). A calibrated model may be used in a model predictive controller for irrigation management and to provide feedback data in evaluations of control strategies in the simulation environment (McCarthy 2010).

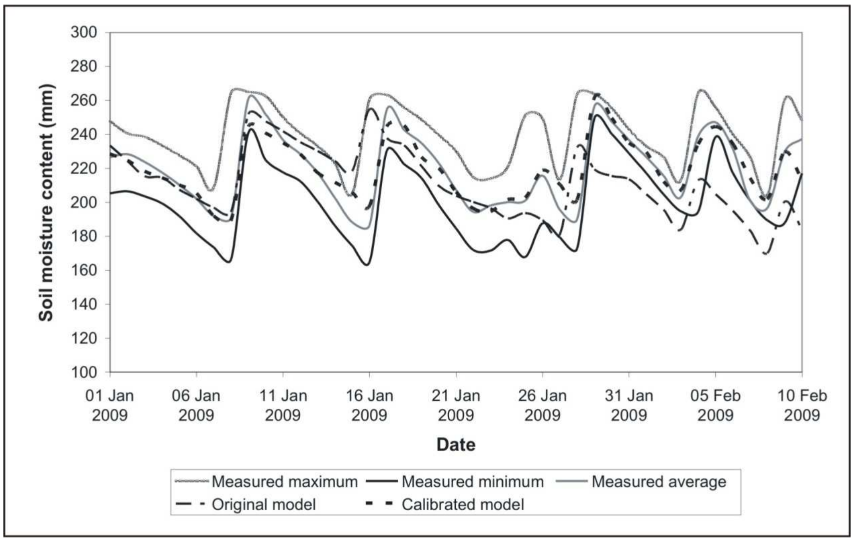

Fig. 3. Measured and modelled soil moisture data for three replicates of irrigation treatment

Practical implementation

As noted, an adaptive control system implemented on an irrigation machine must be robust to intermittent data availability and accommodate spatial variability. We suggest this may be achieved by utilising site-specific combinations of plant, soil and weather data in different sub-areas of the field. Likewise, adaptive system identification may be incorporated into an irrigation control system to account for the slow speed of crop dynamics and the frequency of irrigation events. To meet these requirements and circumvent the limitations set out above, an alternative approach has been successfully implemented (McCarthy 2010). Its two major aspects are as follows.

1. Adaptive interpolation of system inputs

Certain essential inputs may consist of only one data value for the whole field (e.g. rainfall), and others may comprise point measurements scattered sparsely across the field (e.g. soil moisture). For the latter spatially distributed values are estimated by kriging (i.e. spatially interpolating) across the field such that an appropriate data value is then assigned to each sub-area in the field.

Unfortunately, experience indicates that in-field sensors may also be unreliable and fail to measure or transmit data as required. The proposed irrigation control system will then use the best available combination of sensed weather, soil and plant data to determine local irrigation application amounts in each sub-area of the field. Table 1 displays the data input combinations employed according to what data is available. For example, if an irrigation control system uses the plant height and soil moisture to determine the irrigation application and the plant data is not available, then the soil moisture data alone is used to determine the irrigation (e.g. by applying the volume that will fill the soil deficit). A strategy using weather data determines the irrigation application by estimating the crop evaporation and transpiration (i.e. evapotranspiration), whilst a strategy using plant data determines the irrigation application that maximises the reproductive growth and/or maintains the vegetative growth. In Table 1, 'averaged weather' involves using historical weather data representative of the time of the year and is re-estimated daily.

Table 1: Data inputs used for control with limited data availability

User-specified input variable/s for control	**Input variable/s for control with unavailable data**		
	No plant data	**No soil data**	**No weather data**
Weather	N/A	N/A	Averaged weather
Soil	N/A	Averaged weather	N/A
Plant	Averaged weather	N/A	N/A
Weather AND soil	N/A	Weather	Soil
Weather AND plant	Weather	N/A	Plant
Soil AND plant	Soil	Plant	N/A
Weather AND soil AND plant	Weather AND soil	Weather AND plant	Soil AND plant

2. Adaptive spatially-varied identification

The efficiency of control systems may be improved for irrigation by evaluating a range of inputs to the system at each irrigation event (i.e. applying and evaluating a range of irrigation volumes on different sub-areas or 'cells' in the field). An iterative hill climbing algorithm has been developed (McCarthy et al., 2010) and evaluated in the simulation environment. It involves the following process:

1. The field is divided into zones according to a pre-measured variability map.
2. 'Test cells' are selected in each zone to evaluate different irrigation volumes.
3. Test irrigation volumes are applied to each test cell.
4. Before the next irrigation is applied the crop response to the previous irrigation volume is evaluated. A performance index is calculated for each test cell in each zone. The irrigation volume applied to the test cell with the highest performance index is applied to the whole zone.
5. Steps 3 and 4 are repeated for each irrigation event. New test cells are also selected in each zone after each irrigation event to ensure that the response of a test cell is indicative of the rest of the zone.

Conclusion

Adaptive control strategies applied to irrigation management can potentially optimise irrigation water use and/or crop yield. The difficulties in applying classical control systems may be overcome by utilising control strategies which improve the efficiency of system identification, estimate unknown spatial field data and accommodate constraints in the water available for application.

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